Marine Boundary Layer Cloud-top Altitude Analysis from Satellite Measurements

Mary S. Jordan and Philip A. Durkee

Department of Meteorology
Naval Postgraduate School
589 Dyer Rd., Room 254
Monterey, CA 93943-5114
Phone: 831-656-3109
Fax: 831-656-3061
jordan@nps.navy.mil

1. INTRODUCTION

Knowledge of refractivity conditions in the open ocean and littoral regions is important for force protection and strike capabilities. In the marine boundary layer, the top of the stratocumulus cloud deck occurs at the base of the inversion. This is also the location of the Optimum Coupling Height (OCH) for elevated ducts (Helvey, 2000). Personnel at the Naval Air Warfare Center Weapons Division, Pt. Mugu, NAS, have investigated techniques to predict the EM/EO environment from satellite, synoptic and in-situ data sources (Rosenthal, et. al, 1997). The first step in the process to estimate refractivity conditions from satellite imagery is to accurately estimate the marine stratus cloud-top height.

The cloud-top height estimation technique described here was developed as part of the **S**atellite-Derived Marine Atmospheric Boundary Layer and **EM/EO** Properties (SEMEO) project at NPS. The purpose of SEMEO is to estimate the location and strength of elevated ducts in coastal and open ocean regions using AVHRR and GOES imagery in one automated process.

In a well-mixed stratocumulus-topped boundary layer (STBL), without cloud decoupling and with only a small air-sea temperature difference, the observed temperature difference, ΔT, between the cloud top and sea surface, and the cloud-top height, $Z_{CloudTop}$, can be used to estimate the overall STBL lapse rate, $\Gamma = \Delta T/Z_{CloudTop}$. If the boundary layer is well-mixed but cloud-free, the temperature difference divided by the boundary layer depth would approximate the dry adiabatic lapse rate. If clouds filled the entire depth of the boundary layer, the overall STBL lapse rate would approximate the moist adiabatic lapse rate. In most STBLs, clouds do not fill the entire depth, so there is cloud-free air below the clouds. It is expected that the observed $\Delta T/Z_{CloudTop}$ lapse rate would be between the dry and moist lapse rates. Studies have indicated a relationship between the temperature gradient, ΔT, and the boundary layer depth, $Z_{CloudTop}$. Larger ΔT is correlated with deeper boundary layers.

The STBL will be adiabatic only under certain conditions (e.g. sufficient turbulence for a well-mixed boundary layer and low surface heating by solar radiation). The STBL meets these two conditions most of the time and an adiabatic or moist adiabatic lapse rate assumption is valid (McBride, 2000). The dry adiabatic lapse rate, approximately -9.8C/km, is the rate at which the air temperature decreases with height for an unsaturated air parcel. The moist adiabatic lapse rate is the air temperature decrease with height for a saturated parcel. This lapse rate is nonlinear, but since the STBL rarely exceeds 1.5 km in height, a constant value is used.

An STBL forms in response to the interaction between the cool air near the sea surface and warm, subsiding air aloft. The resulting turbulent mixing generates a steady-state, well-mixed STBL with a small air-sea temperature difference. When these conditions are met, the cloud-top and SST temperature difference, ΔT, and cloud-top height are well correlated. Once the STBL is formed, other meteorological and oceanographic processes may occur which make the measured ΔT slightly less correlated with cloud-top height. Upwelling of cold water or advection of warm air over cooler water increases the air-sea temperature difference, but the temperature difference may not immediately affect the depth of the boundary layer. Advection of air into the boundary layer and cloud entrainment can change the lapse rate in portions of the STBL. Cloud decoupling can occur in the boundary layer. In these cases, the effective lapse rate within the STBL may not be estimated accurately by $\Delta T/Z_{CloudTop}$.

2. CLOUD-TOP HEIGHT ALGORITHM

The Naval Postgraduate School (NPS) has designed a physically-based model to estimate cloud-top height of marine stratus using AVHRR or GOES infrared (channel 4) cloud-top temperature and the corresponding surface temperature measurement (McBride, 2000). This technique assumes the following:

1. Boundary layer is well-mixed.
2. The air-sea temperature difference is small.
3. Stratus clouds have not decoupled from the boundary layer.
4. The percentage of the boundary layer depth which contains cloud (vertical cloud fraction) is constant.
   - Deep boundary layers (> 400 m): top 1/3 is cloud, bottom 2/3 is cloud-free.
   - Shallow boundary layers (<400 m): top 2/3 is cloud, bottom 1/3 is cloud-free.

Figure 1 illustrates the NPS technique, which uses known values of surface temperature (T_S) and infrared cloud-top temperature (T_{CT}) and an assumed vertical cloud fraction to compute the boundary layer depth, using the dry adiabatic lapse rate in the cloud-free portion, from the surface to cloud base, and a pseudo-adiabatic lapse rate of in the clouds.

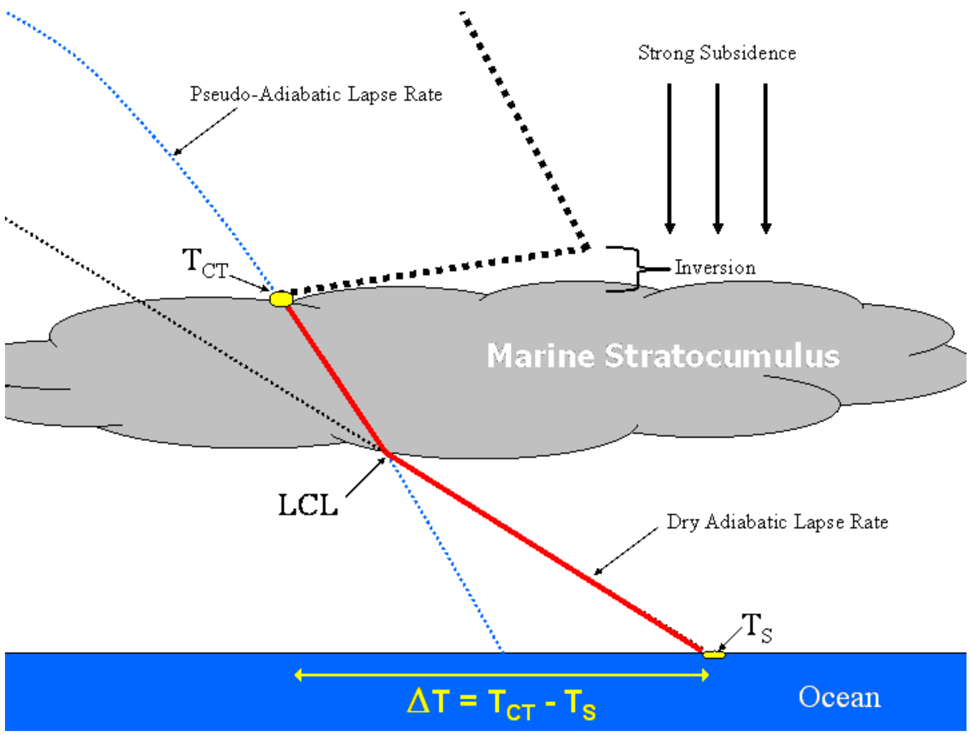

Figure 1. Surface temperature (T_S) and satellite infrared cloud-top temperature (T_{CT}) are known values. The lifted condensation level (LCL) is the base of the cloud. The dry adiabatic lapse rate is used in the cloud-free region and the pseudo-adiabatic lapse rate is used in cloud.

The steps of the NPS technique are listed below:

1. Define the temperature difference between the cloud-top and surface.

$$\Delta T = T_{CT} - T_S \tag{1}$$

2. Using the measured ΔT and the dry adiabatic lapse rate (-9.84 C/km), estimate the boundary layer depth with no clouds (all temperatures in °C, lapse rates in °C/m, heights in meters).

$$Z_{dry} = \Delta T \ / \ \Gamma_{dry} \tag{2}$$

3. Assuming a vertical cloud fraction of 1/3 (meaning 2/3 is cloud-free), compute the height of the cloud base for a 2/3 cloud-free boundary layer.

$$Z_{CloudBase} = 2/3 * Z_{dry} \tag{3}$$

4. Using the dry adiabatic lapse rate, Γ_{dry}, and the surface temperature, T_S, compute the cloud-base temperature for a 2/3 cloud-free boundary layer.

$$T_{CloudBase} = (\Gamma_{dry} * Z_{CloudBase}) + T_S \tag{4}$$

5. Using the measured cloud-top temperature, T_{CT}, the cloud-base temperature, $T_{CloudBase}$, and the pseudo-adiabatic lapse rate, Γ_{moist} (-7.0 C/km), compute the cloud depth (m).

$$CloudDepth = (T_{CT} - T_{CloudBase}) * \Gamma_{moist} \tag{5}$$

6. Compute the cloud-top height (m), $Z_{CloudTop,}$ using the cloud-base height and cloud depth.

$$Z_{CloudTop} = Z_{CloudBase} + CloudDepth \tag{6}$$

7. If the cloud-top height is less than 400 meters, recompute the cloud-top height using an assumption of 2/3 vertical cloud fraction (meaning 1/3 is cloud-free). Use Equation 3 with a cloud-free ratio of 1/3 vice 2/3. Using the new cloud-base height, use Equations 4-6 to generate a new, higher estimate of cloud-top height. In Step 5, use the pseudo-adiabatic lapse rate, Γ_{moist} = -6.5C/km. The rationale for recomputing cloud-top height is that shallow STBLs typically have a higher vertical cloud fraction. The 400m break point was determined from observations by McBride (2000).

To speed up pixel-by-pixel computations in a cloud scene, both the deep and shallow case estimates of cloud-top height are computed simultaneously. A check of the heights is made and when the height computed using the deep STBL assumptions is less than 400 meters the shallow-case height is substituted.

3. VERIFICATION CASES

A total of 53 cases were selected from three marine stratocumulus experiments off the central and southern California coasts. The Marine Stratocumulus Intensive Field Observations phase of the First International Satellite Cloud Climatology Project Regional Experiment (FIRE) occurred 29 June - 19 July 1987 off the coast of southern California. Nine of the aircraft spiral soundings from this data set were chosen based on NOAA-10 AVHRR satellite imagery and sea-surface temperature (SST) measurement availability. Air temperature measurements at low levels are not available because the aircraft did not fly below about 75 meters.

The Monterey Area Ship Track (MAST) experiment occurred 3-29 June 1994 off the central California Coast. Fifteen MAST cases were selected and used NOAA-9, 11, or 12 AVHRR imagery. In ten of the 15 MAST cases, sea-surface temperatures were available and used. For the remaining five cases, the rawinsonde air temperature, measured at 3 meters, was used in place of the SST.

Twenty-nine cases from the Cloud-Aerosol Research in the Marine Atmosphere (CARMA) experiment off the central California coast, 19 August - 6 September 2002, were selected and used satellite imagery from polar orbiter (NOAA-16, 17) and geostationary (GOES-10). The vertical profiles were produced by aircraft spiral profiles down to about 50 meters above the ocean surface. The NAVO Multi-Channel Sea-Surface Temperature (MCSST) "K10" product, which is a global 1/10th degree gridded satellite SST composite updated daily from Polar-orbiting Operational Environmental Satellites, was used as the surface temperature in the CARMA cases.

Figure 2 shows the locations of the rawinsondes or aircraft profile soundings for the FIRE, MAST and CARMA cases along the California coast. For many of the CARMA soundings, multiple satellite images were verified by the same sounding.

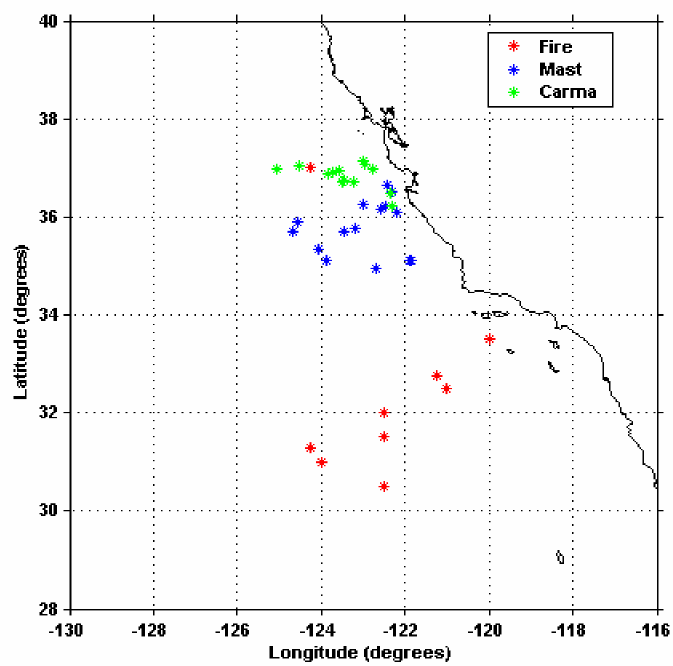

Figure 2. The locations of the rawinsondes or aircraft profile soundings for the FIRE, MAST and CARMA cases along the California coast.

Figures 3-5 provide an example of the cloud-top height algorithm applied to a GOES-10 satellite image. The visible image (channel 1) for 1915 UTC 28 August 2002 is shown in Figure 3 and the blue dot indicates the location of the aircraft spiral profile. The full resolution visible image has 1-km resolution, but is mapped in Figure 3 onto a 4-km mercator resolution because the infrared (channel 4) temperature has a 4-km resolution. The aircraft profile is in a marine stratus layer with some variation in reflectance but the thermal (channel 4) temperatures vary by less than 0.5 C over 1000 km^2 around the aircraft profile. Figure 4 shows the 0.1 degree resolution NAVO "K10" SST gridded field displayed on a 4-km mercator projection. The aircraft profile location, denoted on the image by a square, is near a region with a strong SST gradient (cooler water north and east).

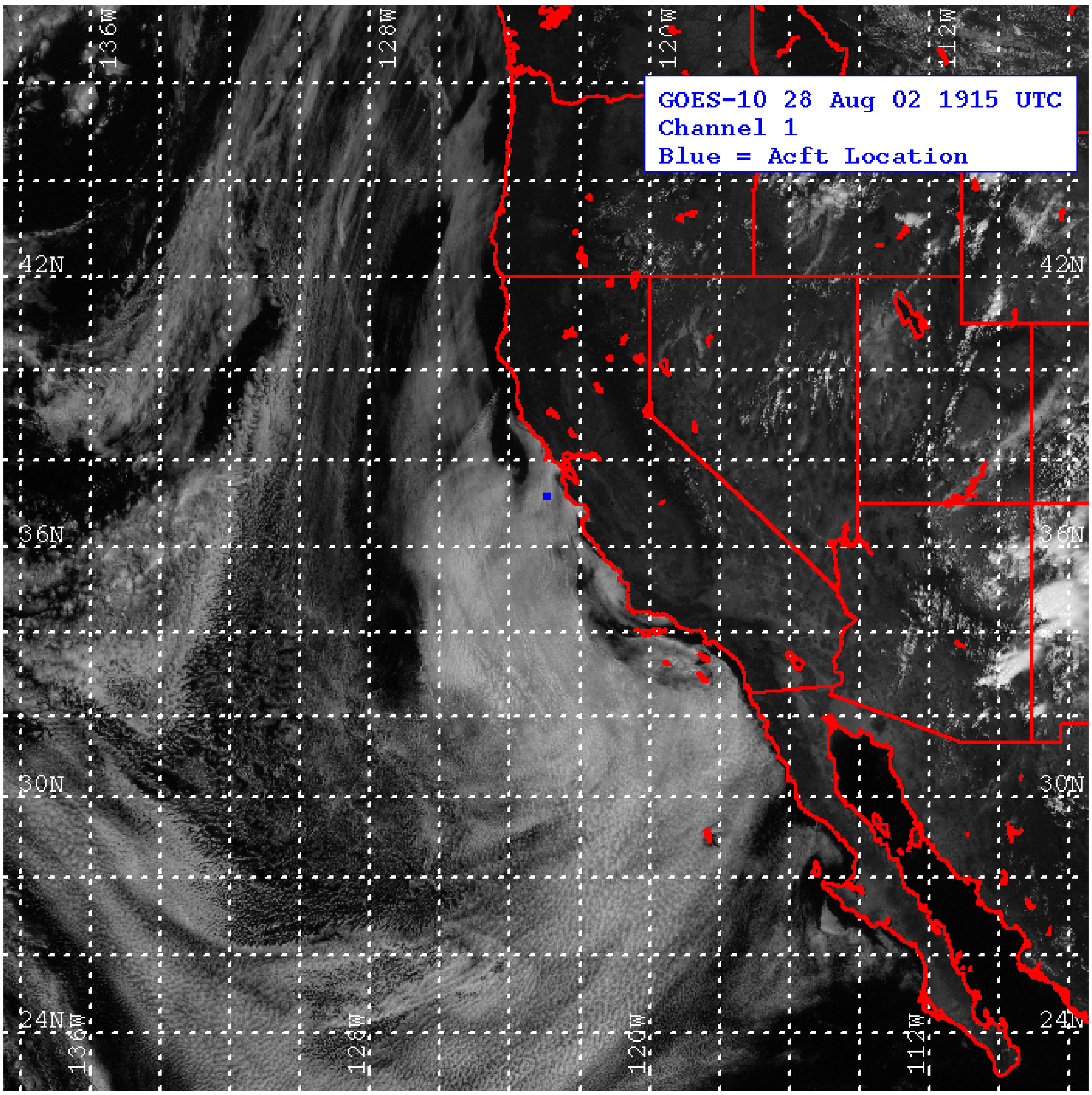

Figure 3. GOES-10 1915 UTC 28 August 2002 visible (channel 1) image mapped onto a 4-km mercator projection. The approximate location of the aircraft profile, taken at 1930 UTC, is denoted by the blue dot.

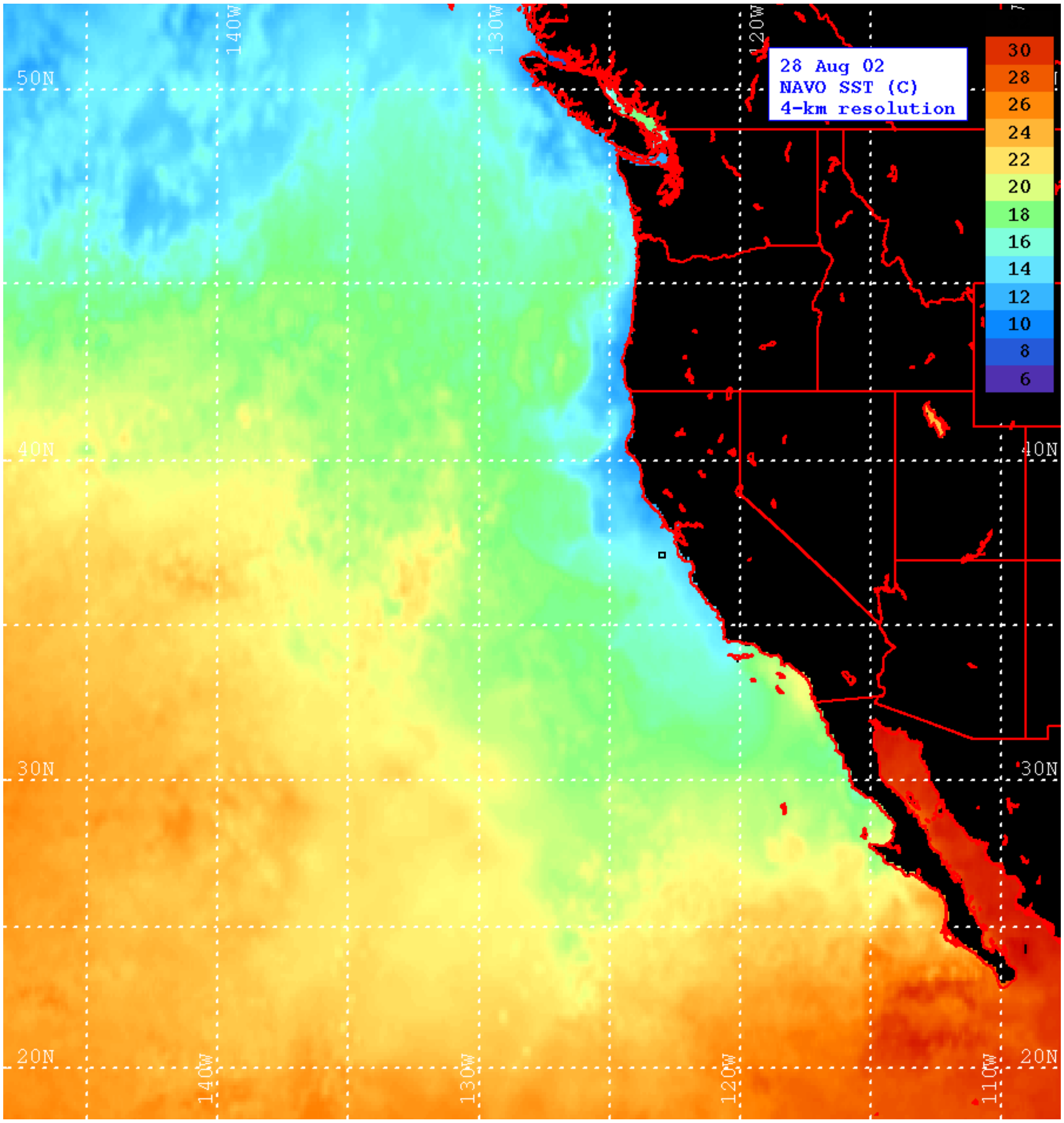

Figure 4. The 0.1 degree resolution NAVO “K10” SST gridded field for 28 August 2002 mapped to a 4-km mercator projection (with a larger domain than in Fig. 3). The aircraft profile location, denoted on the image by a square, is near a region with a strong SST gradient (cooler water north and east).

The NPS cloud-top algorithm was applied to the entire marine stratus region, pixel-by-pixel, using the channel 4 brightness temperatures and the NAVO SST analysis. Figure 5 shows the resultant cloud-top height estimate overlaid on the aircraft vertical profile of temperature and dew point temperature. The time difference between the satellite image and the aircraft profile (1930 UTC) is 15 minutes. The temperature at the base of the inversion in the aircraft sounding is 11.9 C and the satellite cloud-top temperature is 11.3 C. The SST of the pixel corresponding to the profile location is 14.7 C. The result of technique Steps 1-6, which assumes the cloud occupies only 1/3 of the boundary layer, is a cloud-top height estimate of 395.7 m. Since this height estimate is less than 400 m, Step 7 is applied and the height is recomputed using an assumption of vertical cloud fraction of 2/3. The recomputed height estimate is 468.0 m. The verification cloud-top height from the sounding is 477.9 m. In Fig. 5, the surface temperature (T_S), cloud base temperature and height estimated from the NPS technique (shown as the LCL in Fig. 1) and the cloud-top height estimate and satellite temperature (T_{CT}) is plotted in red, along with straight lines between the three points, to help visualize the lapse rate.

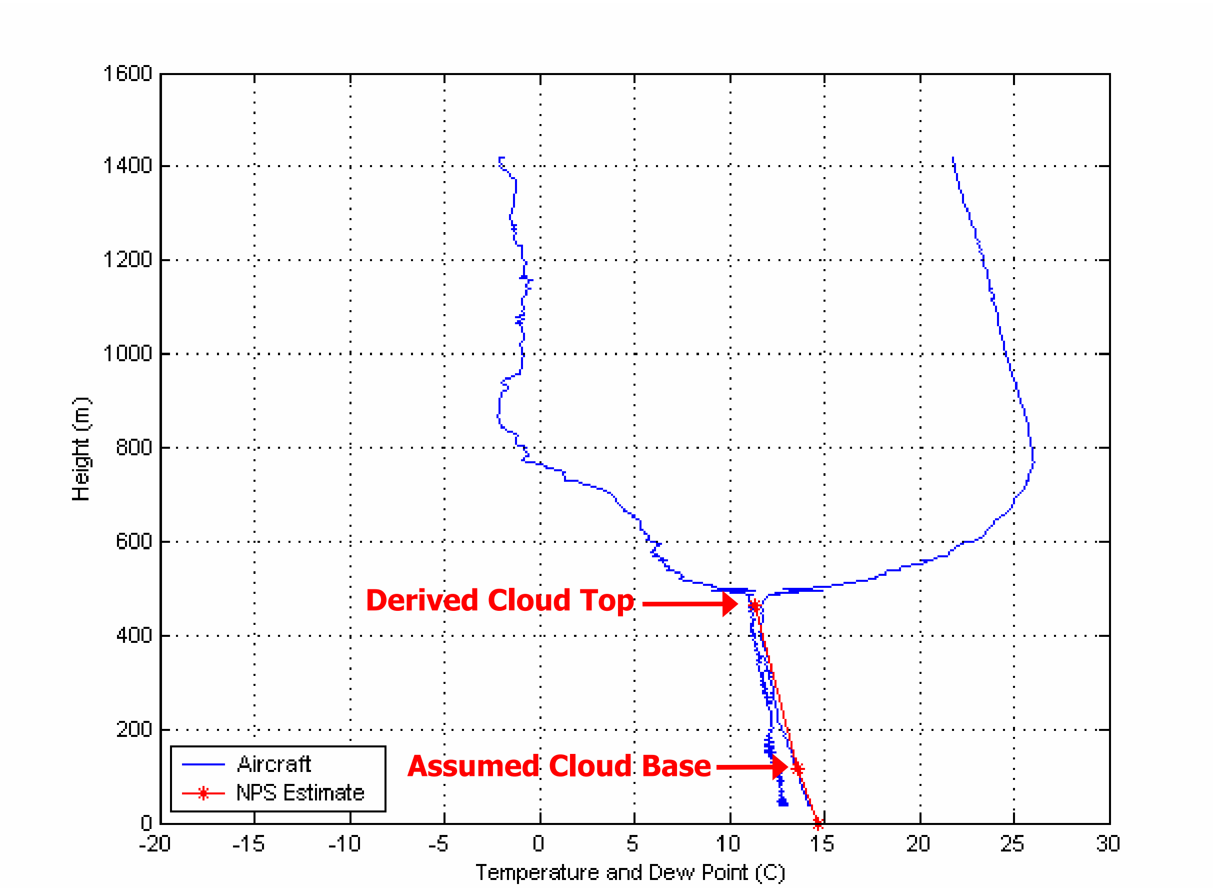

Figure 5. Aircraft temperature (C) and dew point (C) profile for 1930 UTC 28 September 2002 is the blue line. The NPS estimate of cloud-top height (m), computed using input satellite marine stratus cloud-top temperature from the GOES-10 1915 UTC 28 September 2002 image and corresponding NAVO SST analysis, is indicated by the uppermost red star in the figure. The SST and assumed cloud base temperature and height are also plotted. A straight line is plotted between the cloud base and top, even though the pseudo-adiabatic lapse rate is nonlinear. The estimated cloud-top height is 468.0 m and the verification cloud-top height from the sounding is 477.9 m.

4. RESULTS

Figure 6 shows the compares the cloud-top height (m) estimate using the NPS technique with the measured cloud-top height (base of the inversion) from rawinsonde or aircraft profile for the 53 cases from FIRE, MAST and CARMA. The MAST cases have higher error for shallow boundary layers (< 400 m). In the CARMA cases, there are instances where the air-sea temperature difference is not small and this contributes to error.

The RMS difference between the measured and estimated cloud-top heights is listed in Table 1. The RMS height difference is the lowest for the FIRE cases and this may be due to the stratus forming in a region without upwelling. Some of the MAST and CARMA cases were in regions with upwelling and the corresponding strong SST gradients. This may have contributed to instances where the boundary layer developed over colder SSTs and advected into a region with higher SSTs (or vice versa). Consequently, the SST used in the technique was not representative of the surface temperatures which occurred during formation of the boundary layer – and the estimated cloud-top height has additional inaccuracies.

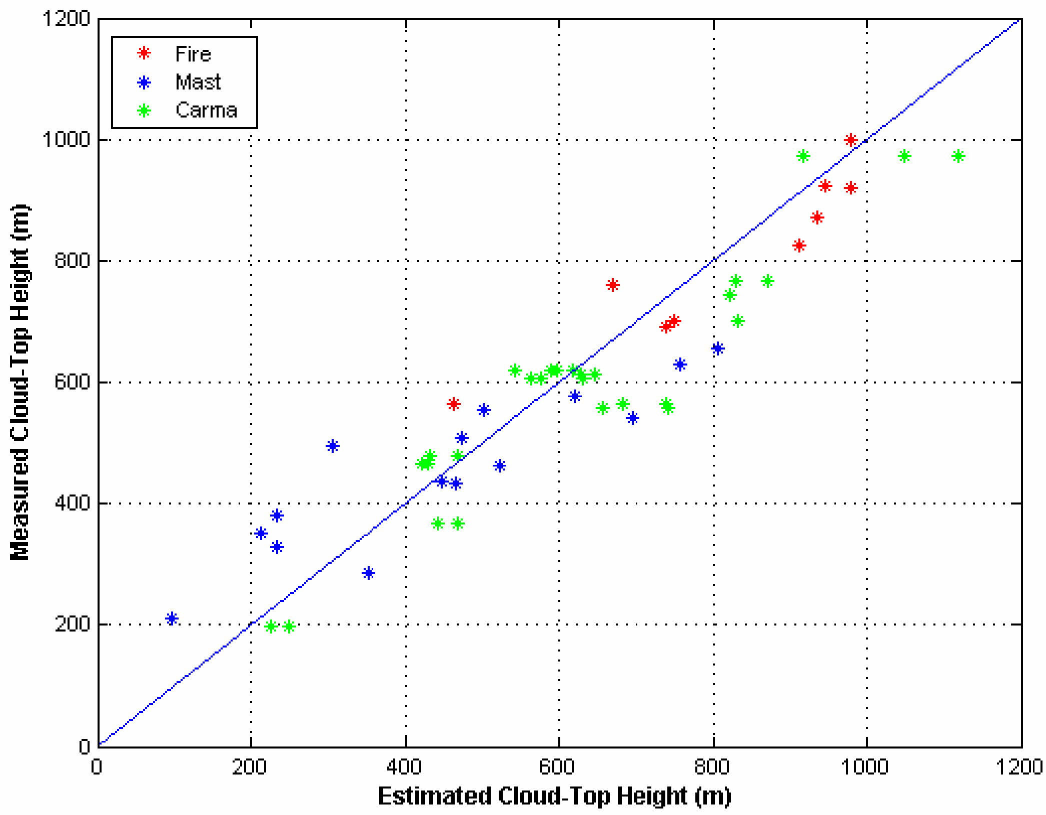

Figure 6. Verification of the cloud-top height (m) estimate using the NPS technique versus the measured cloud-top height (base of the inversion) from rawinsonde or aircraft profile for the 53 cases from FIRE (red) , MAST (blue) and CARMA (green). A one-to-one line is plotted in blue.

Table 1. RMS height difference between the measured and observed cloud-top height (m), and RMS temperature difference between measured cloud-top (inversion base) temperature and satellite cloud-top temperature (C).

Experiment	RMS Height Difference	RMS Temperature Difference
FIRE	66.2 m	0.45 C
MAST	108.6 m	0.33 C
CARMA	81.8 m	1.01 C
All 53 Cases	88.0 m	0.80 C

5. SUMMARY AND FUTURE WORK

The 88 m RMS cloud-top height difference is a promising result. There was good agreement in the CARMA cases between AVHRR and GOES height estimates on each day. In general, the cases were selected to match the technique assumptions, but a few CARMA cases have a significant air-sea temperature difference. These cases illustrate an issue for future research – improve the surface temperature estimate so the input temperature more closely matches the temperature which occurred during boundary layer formation. One option is to investigate enhancements to the NAVO MCSST, which may have old temperatures if the stratus has been in the same location for several days. Additionally, computation of a weighted average of the surface temperature for each pixel, using a backwards trajectory, would provide an estimate of the temperature which generated the boundary layer.

6. ACKNOWLEDGEMENTS

The authors wish to thank SPAWAR for SEMEO funding, Dr. Haflidi Jonsson, NPS Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS), for providing the CARMA aircraft data, and Mr. Roger Helvey, NAWC Pt. Mugu NAS, for sharing his experience on methods to estimate refractivity conditions from satellite imagery and synoptic conditions.

7. REFERENCES

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